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A short-term based analysis on the critical low carbon technologies for the main energy-intensive industries in China

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ABSTRACT

The thermal power industry, the cement industry and the iron & steel industry are among the top energy consumers and air-polluters in China, which have significant impacts on climate change. The annual productions of these three industry sectors are all ranked as the top one in the world. In order to assist the short-term policy making for the development of critical LCTs in China, an evaluation of the performance of low carbon technologies (LCTs) for the top three energy-intensive industries in China is conducted in this paper through multi-criteria decision making (MCDM) method. There are 31 LCTs identified for these three industries based on the criteria including environmental performance, technological performance, and economic performance. Based on the experts' evaluation, top 10 LCTs are selected as the critical LCTs which should be given priority in the short-term technology diffusion in China. Suggestions are provided for policy-makers on the carbon mitigation and cleaner production in the main energy-intensive industries in China.

1. Introduction

As the largest energy consumer and the second largest economy in the world (BP, 2015), China plays an important role in fighting climate change and reducing carbon emissions. In 2015, China submitted the Intended Nationally Determined Contributions (INDC) to the United Nations Framework Convention on Climate Change (UNFCCC), and set a target to cut down carbon emissions by 60–65% per unit of GDP by 2030. The ambitious carbon mitigation target of the Chinese government put great pressure on those energy-intensive industries in China, such as the thermal power industry, the cement industry and the iron & steel industry, which are also the key economic pillar industries in China (Jim et al., 2015; Li et al., 2013, 2014). According to China Statistics Yearbook 2016 (National Development and Reform Commission of China, 2016), the energy consumption of the three energy-intensive industries alone accounted for 29% of total energy consumption in 2015. Despite the great efforts that China has paid to carbon mitigation, there is still large room for carbon mitigation in those major energy-intensive industries (Wang and Chang, 2014a).

The power generation sector, as one of major sources of Green House Gas (GHG) emissions, consumes a large quantity of fossil fuels every year in China (Liu et al., 2009; Chang and Wang, 2010). Since 2006, Although the percentage of thermal power generation in the total power generation has decreased since 2006, its generation capacity has been increasing quickly during the same period, as shown in Fig. 1. Ranking as the top 1 in the world, the Chinese power industry generated 5811 Terawatt-hours electricity in 2015, accounting for 24.1% of the world's total power generation (BP, 2016). According to *China Electric Power Industry Annual Development Report 2016* released by the China Electricity Council, the overall installed power generating capacity has reached 1.52 billion kilowatts by the end of 2015, in which the installed capacity of thermal power was 1.00 billion kilowatts, accounting for 65.92% of total capacity (China Electricity Council, 2016).

Although the renewable energy technologies, such as hydropower, wind and solar power, have developed rapidly during the past decades, thermal power is the primary source for power generation in China. As Xie et al. (2012) pointed out, the thermal power, especially coal-fired-power, remained as the most dominating form of energy generation, accounting for more than 70% of total energy consumption (Xie et al., 2012).

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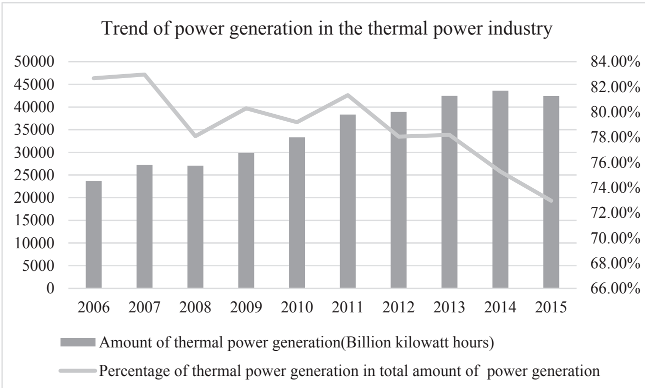

Fig. 1. The trend of power generation in the thermal power industry.

Another large energy consumer in China is the cement industry, which has also been identified as a critical emitter of air pollutant and environmental destroyer due to its contribution to Particulate Matter (PM), SO_2 and NO_x emission (Lei et al., 2011; Zhang et al., 2007; Ke et al., 2012). In China, the cement industry consumes 5%–8% of the country' total energy, and emits 15% of total GHG (Wen et al., 2015; Chen et al., 2014; Zhang et al., 2015a). Between 2006 and 2015, the cement production in China doubled as shown in Fig. 2. The cement production of China in 2016 was 2.41 billion tons, accounting for 57.38% of world cement production and ranked first in the world. China's clinker production was 200 million tons in 2016, accounting for 54.05% of world's cement clinker production and ranked the first in the world (U.S. Geological Survey, 2017).

Due to its carbon-based metallurgy, the iron & steel industry has become one of the largest energy consumer and the third biggest CO_2 emitter in China (Zeng et al., 2009). In 2015, China's crude steel production reached 803.8 million tons, accounting for 49.6% of world crude steel production and ranked the first in the world (World Steel Association, 2016). According to the 2015 National Economic and Social Development Statistics Bulletin and the China Statistics Yearbook 2016 (National Bureau of Statistics of the People's Republic of China, 2015; National Development and Reform Commission of China, 2016), China's total energy consumption had reached 4.3 billion tons of standard coal in 2014. The biggest contributor was the Black Metal Smelting and Rolling Processing Sector, consuming 693.4 million tons of standard coal. This sector alone accounted for 16.3% of national energy consumption and ranked first in all the industry sectors. Within the Black Metal Smelting and Rolling Processing Sector, the majority of productivity came from the iron & steel industry (CHYXX, 2016).

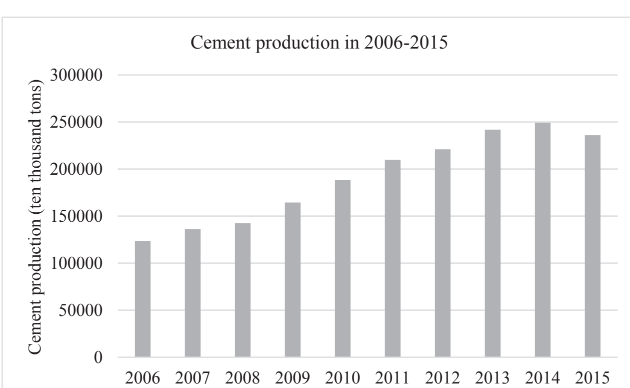

Fig. 2. Cement production of China in 2006–2015.

In recent years, the government has adopted a series of policies to promote LCTs and clean production in the energy-intensive industries (Wang and Chang, 2014b). The relevant policy and documentations in recent years are listed in Table 1 below.

Those government policies are mostly designed for the long-term development plan. However, there is a lack of short-term development guidance for the key energy-intensive industries such as the thermal power industry, the cement industry and the iron & steel industry. Due to the rapid technology development and upgrading speed, it is more meaningful to discuss the short-term strategies in LCTs diffusion than long-term ones. The determination of critical LCTs would assist policy-makers and industrial practitioners in China to conduct immediate promotion on the appropriate LCTs, and achieve low carbon development in a more effective way. The top energy-intensive industries in China, which consume extensively more energy than other industries, are considered to be of both low energy-efficiency and high carbon emissions (Li et al., 2014). As a developing country, China determines to achieve the carbon reduction target; however, it would never want to jeopardize industry capacity. It is, therefore, necessary to discuss the short-term strategies for carbon reduction plan including promoting of critical and effective low carbon technologies (LCTs) for these energy-intensity industries. The major challenge for the government would be transforming those large carbon emitters to cleaner production.

In order to achieve China's ambitious carbon reduction targets in a more efficient way, it is important to identify the critical LCTs for the energy-intensive and economic-significant industries. This paper sheds a light on the selection of the most critical LCTs to reduce carbon emissions in these three energy-intensive industries under a five-year short-term development view. The results can assist the short-term policy making for the government in targeting carbon emission for these energy-intensive industries in China.

2. Literature review

2.1. The role of LCTs

The role of LCTs in low carbon development and clean productions for energy-intensive industries had been discussed by researchers (Kemp and Volpi, 2008; Weyant, 2011; Wang and Chang, 2014b). For example, Pavic et al. (2016) considered that low carbon technologies (LCTs) were the essential link in the creation of sustainable energy future, redefines operation and planning concepts of traditional energy systems. Montalvo (2008) also stressed the importance of low carbon technologies in clean production and achieving low carbon target. In the research of He et al. (2012) discovered that the innovation of advanced LCTs was the foundation of low-carbon development and helped countries to enhance competitiveness in global market.

In the developing world, the LCT related topic also received great attention. Researchers Khosla et al. (2017) indicated the importance of low-carbon technology development and transfer for developing countries to assist in their growth, whilst fulfilling global climate objectives. Jacobsson and Bergek (2004) interpreted that technological innovation aiming for carbon reduction might lead to a complete transformation of the carbon-based socio-technical system. Qian (2012) believed that the transferring of LCTs from developed countries to developing countries could assist developing countries to reduce carbon emissions. Kennedy and Basu (2013) pointed out that LCTs could play a central role in meeting climate objectives, by exploiting sources of energy and allowing cheaper, cleaner and more efficient methods of converting energy into desired end use services. Furthermore, the importance of public support in LCT development was stressed by researcher

Table 1
Recent policies and documents for carbon reduction technology in China.

Policies	Launching organizations	Year
China's Medium and Long-term Scientific and Technological Development Plan (2006–2020)	State Council of the People's Republic of China	2006
National Scheme Technology Actions Program for Energy Saving and Emission Reduction	Seventeen departments of China	2007
2014–2015 Energy Saving and Emission Reduction Technology Special Action Program	Ministry of Science and Technology of the People's Republic of China & Ministry of Industry and Information Technology of the People's Republic of China	2014
National Plan on Fighting Climate Change (2014–2020)	National Development and Reform Commission (NDRC) of China	2014
National Extension Directory of the Key Energy Conservation Technology of China (2015)	National Development and Reform Commission (NDRC) of China	2015

Cherry et al. (2014), who stated that large-scale deployment of low-carbon energy technologies was crucial to mitigating climate change and public support was a key barrier to the development and deployment of low-carbon technologies. Although the above researches have emphasised the importance of LCR, they did not identify the critical LCTs for developing countries.

In terms of China, the National Development and Reform Commission (NDRC) of China suggested that the coal industry, the electricity industry, the iron & steel industry and other high energy-consuming industries should adopt, promote the advanced energy-saving technologies and LCTs in order to reduce energy consumption and release environmental pressure (National Development and Reform Commission of China, 2015). For a certain industry, there are a large number of LCTs available, whose effectiveness is of difference. The critical LCTs would have better performance in carbon reduction. The effectiveness of LCTs, however, may change in a long period under the rapid technology innovation process. It is more reasonable to focus on comparison between the critical LCTs for each of the energy-intensive industries within a short-term analytic period.

2.2. The effectiveness of LCTs

The effectiveness of LCTs also attracted the attention of researchers in different countries. In a research focusing on the thermal power industry, Chikkatur and Sagar (2009) claimed that the use of Supercritical and Ultra-supercritical Technology were perhaps the most relevant for India to achieve carbon mitigation. The research of Morrow et al. (2008) in the U.S. showed that the co-firing 189 million dry short tons of switchgrass with coal in the U.S. coal-fired electricity generation fleet could mitigate approximately 256 million short tons of carbon-dioxide per year. Their research demonstrated that co-firing switchgrass and coal were a perfect method to reduce CO_2 emissions from existing coal-fired power plants in the U.S. Cho et al. (2014) stated that Combined Cooling, Heating, and Power Systems in the traditional power plants had the potential to increase resource energy efficiency and to reduce air pollutant emissions dramatically.

Researches on the LCTs in the cement industry had also been carried out, for example Cai et al. (2008) applied the Long-rang Energy Alternative Planning System Model to estimate quantitatively CO_2 mitigation potential in China. Their results revealed that the 'Conversion to Multi-stage Pre-heater Kiln' and 'Combustion System Improvement' had the highest mitigation potentials by 2020. The results of Xu et al. (2014) showed the feasibility to achieve the International Energy Agency cement technology roadmap up to 2050 through applying current best available technologies, including Clinker Substitution, CCUS, Energy Efficiency Improvement and alternative fuels. Wen et al. (2015) applied the Asian-Pacific Integrated Model to evaluate the potential for CO_2 emissions reduction in China's cement industry between 2010 and 2020. Although they did not identify the specific critical technologies as Xu et al., their literature suggested that LCTs promotion and sector structure adjustment were the main measures to reduce carbon emissions.

In the LCTs study for the iron & steel industry, there were few researchers contributing to the evaluation of LCTs. Zeng et al. (2009) suggested that Reusing of Waste Heat, Pressure and Furnace Gas were suitable CO_2 emission-reducing technologies in China. Liu and Gao (2016) indicated that Dry Top Pressure Recovery Turbines, Sintering Waste Heat Recovery Power Generation and Energy Management Centers were three critical energy saving technologies and LCTs to reduce carbon emissions in China' iron & steel industry. Although the two researches both discussed the LCTs for the iron & steel industry in China, they were carried out at different time period and result in different preferences. However, a research based on European circumstances showed a different priority on LTCs selection, where they investigated several breakthrough technologies for the drastic reduction of CO_2 emissions under the European Ultra Low CO_2 Steelmaking Program in the iron & steel industry (Quader et al., 2015a). The results showed that the implementation of CO_2 Capture and Storage (CCS) technology in coal-based integrated steel plants might reduce 80% of CO_2 emissions. Furthermore, Quader et al. (2015b) concluded that further significant CO_2 reduction could only be achieved by developing and applying CO_2 breakthrough technologies, including the Use of Renewable Energy (Bioenergy), CCS Technology combined with Pure Oxygen Top Gas Recycling Blast Furnace, New Iron and Steel Making Processes, Hydrogen-based Steel Making, Iron-ore Electrolysis and Biomass based Steel Production.

The LCTs for the three energy-intensive industries have attracted the attention of researchers. However various researches in different countries showed different preferences on LCTs due to the existing energy structure, the technology availability and the economic status.

2.3. The technology diffusion

Although the importance of LCTs to low carbon development has been widely acknowledged worldwide, there are still issues in technology diffusion identified by researchers. Iyer et al. (2015) pointed out that global climate required low-carbon technologies; however, the diffusion of such technologies was constrained by institutional, behavioural and social factors. They found that constrains on CCS and renewables were more costly than others. Streimikiene et al. (2016) applied Multi-criteria analysis on various electricity generation technologies in Lithuania to assess their environmental, economic, social and political performance. The result suggests to considering further development and diffusion of the nuclear power generation capacity.

In comparison to the research on the developed countries, the researches on the technology diffusion of LCTs in developing countries identified more macro-level of obstacles. Kennedy and Basu (2013) reviewed and explored the impact of a number of

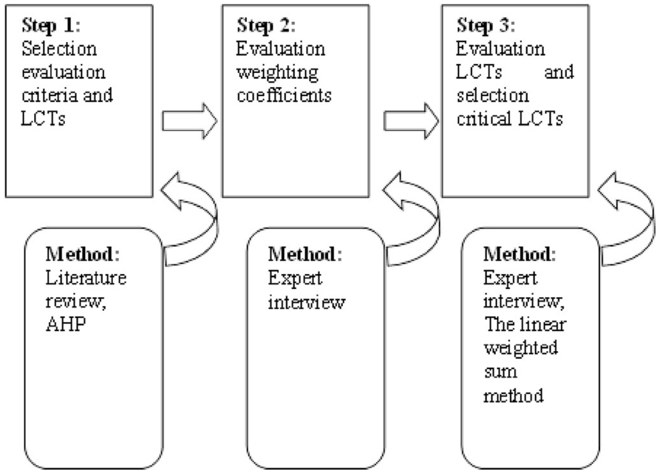

Fig. 3. The analytical framework.

advancing low carbon technology projects in developing and emerging economies, including a Village Power project to East Asia, a regulatory initiative for building energy efficiency in India, a finance advisory network in Africa, a low-energy building programme in China, and an informational initiative targeting the hospitality sector in Fiji, and they identified regulatory, institutional, financial and informational barriers to technology transfer and development. Chen et al. (2011) discussed the prospect for CO_2 emission reduction low-carbon technology roadmap for the power sector in China. The results revealed that converting the current power mix into a low-carbon structure would be critical to mitigate the "carbon lock-in" effects in power sector, thus contributes to CO_2 emission reduction effectively and continuously.

The analysis of literature shows that the preference on LCTs varies in different countries. It is more appropriate to discuss the LCTs selection for individual country rather than a universal discussion, and the study should be based on the technology availability, economic condition, and diffusion barriers of that country.

3. Methodology

3.1. The analytical approach

The Multi-criteria Decision Making (MCDM) method provides analysts with an appropriate way to handle multiple criteria at the same time. It can deal with multiple evaluation criteria in a set of scenario (Thomas et al., 2009. In addition, the MCDM method allows for the combination of political, social and economic criteria within the environment analytical framework (Gamper and Turcanu, 2007; Saaty, 2006). In this research, a MCDM model was established by combining the Analytical Hierarchy Process (AHP) and the linear weighted sum method. The analytical framework is shown in Fig. 3 below. The AHP method was applied to define the criteria for selecting critical LCTs, whilst the linear weighted sum method was introduced to evaluate alternatives against selected criteria.

The alternative LCTs for each of the three energy-intensive industries and the criteria to select critical LCTs were defined after in-depth literature reviews.

3.2. Data analysis

The data collection method for model input was in the form of semi-structured interview survey with relevant experts. There were 41 experts including researchers, industry technical personnel, industry experts and key stakeholders invited to the interview surveys. The experts were selected on the basis of their work experiences and professional knowledge. The invited experts were all age between 30 and 55 years old, with more than six-year work experiences in relevant industries. The statistical analysis of the interviewees is shown in Table 2 below.

The format of the interview survey was face to face meetings, each of which lasts 30–50 min. At the beginning of the interview, the experts were given a brief introduction of the objectives of this study in order to improve accuracy and consistency of the survey. Under the permission of interviewees, the interviews were recorded by digital recorders. The key points in the recordings were then interpreted into Word files format for data extraction.

There were two stage interview surveys carried out by the research team. The objective of the first interview survey was to measure the importance of criteria for selecting critical LCTs. Experts were asked to evaluate each criterion using Blechinger's 5-point Likert scale ranging from "1" for "No importance" to "5" for "Extremely high importance" (Blechinger and Kalim, 2011).

The importance of criterion was represented by weighting coefficient, which was the nominated average of the importance scored by the experts. The calculation of weighting coefficient is showing below.

$$\text{Weightingcoefficient}(i) = Average(C_i) \Big/ \sum_{i=1}^{n} Average(C_i) \qquad (1)$$

where: C_i is the score of the *ith* criterion,*n* is the total number of criteria in MCDM model, *Average* (C_i) is the average of all 41 scores for criterion *i* giving by experts.

In the second stage of expert interview, the experts were asked to assess the effectiveness of alternative LCTs against qualitative criteria. A 5-point scale ranging from "1" for "Not satisfied" to "5" for "Extremely satisfied" recommended by Lootsma was introduced (Lootsma, 1993). The average of the experts' scores was input to the MCDM model to identify the critical LCTs. The evaluation sheets for the two interview surveys were prepared before the survey began.

The quantitative data in the model were collected from the *National Extension Directory of the Key Energy Conservation Technology of China* (National Development and Reform Commission of China, 2015). In order to transfer the quantitative data into the same numerical scale as the qualitative data (1–5), the data were manipulated following formula (2) and (3). For the positive criterion (the bigger the value the better the performance) the quantitative data were then degraded by formula (2). Therefore, for the same quantitative criterion, the LCTs with the lowest value was transfer to the value "1", while the one with the highest value was

Table 2
Statistics of experts' information.

	Classification	Number
Age	20–30	0
	30–40	10
	40–50	23
	50–60	8
Working experiences	6–9	20
	9–12	15
	>12	6
Working sector	The thermal power industry	11
	The cement industry	10
	The iron & steel Industry	12
	Research institute	8
Working title	Professor	6
	Associate professor	2
	Senior Engineer	12
	Engineer	16
	Researcher	5

Table 3
The evaluation criteria list.

Main criteria	Sub-criteria	Literature
Environmental performance (B1)	CO_2 emission reductions (C11)	Li et al., 2013; Heo et al., 2010; Hidalgo et al., 2005;
	Other pollution reductions (C12)	Li et al., 2013; Heo et al., 2010; Cengiz et al., 2009;
	Energy saving (C13)	Streimikiene et al., 2016; Cengiz et al., 2009;
Technological performance (B2)	Technological maturity (C21)	Ren and Lützen, 2015;
	Technological reliability (C22)	Heo et al., 2010; Streimikiene et al., 2016; Cengiz et al., 2009; Akash et al., 1999; Zhang et al., 2015b;
	Technological competitiveness (C23)	Heo et al., 2010; Streimikiene et al., 2016;
Economic performance (B3)	Cost of investment (C31)	Li et al., 2013; Khelifi et al., 2006; Yang et al., 2012; Ren and Lützen, 2015; Zhang et al., 2015b;
	Payback period (C32)	Cooremans, 2011; Zhang et al., 2015b;
	Contribution to fiscal sustainability (C33)	Kathleen and Valerie, 2014;

Table 4
The list of LCTs.

Industry	ID	Technical name
The thermal power industry	A1	Retrofit of flow passage of steam turbines
	A2	Gasification technology of pressurized pulverized coal
	A3	Deep recovery of waste heat from coal-fired power plant flue gas integrated optimization system
	A4	Massive high-parameter lignite (brown) coal powder boiler technology
	A5	The heat-electricity co-generation technical reform on condensing turbine
	A6	Performance improvement of steam turbine generation set
	A7	High efficiency ultra low calorific of coal gangue circulating fluidized bed boiler technology
	A8	Contact sealing technology for rotary air preheater
	A9	Energy-saving and efficiency-improving technology of electrostatic precipitator
	A10	Flue gas and waste heat recovery of deculturation and fun optimization technology
	A11	Energy saving technology of condenser vacuum for power plant
The cement industry	A12	Energy-saving efficient cement grinding technology
	A13	High solid-gas ratio cement suspension preheating and decomposing technique
	A14	Large-thrust and multi-channel combustion energy saving technology
	A15	Cement enterprise visual energy management system
	A16	Energy-saving monitoring and optimization system in the new type dry-process cement rotary kiln
	A17	High efficiency and energy saving powder technology
	A18	Optimization of the cement clinker burning system
	A19	Roller press grinding systems
	A20	Steady pop cement clinker cooling technology
The iron & steel industry	A21	Coal moisture control technology of flue gas
	A22	Flue gas residual-heat utilization technology of ore smelting furnace
	A23	Sintering waste heat power generation technology
	A24	Energy management system
	A25	Energy-saving blast dehumidification technology for blast furnace
	A26	Low heating value blast furnace gas turbine combined cycle power plant
	A27	Large long-term efficient operation of blast furnace top gas recovery turbine unit
	A28	Sintering flue gas recycling technology
	A29	Rotary cutter high blast hot stove energy saving technology
	A30	High temperature and high pressure coke dry quenching device
	A31	Heating furnace blackbody technology to strengthen energy-saving

transferred to value “5”.

$$Si,t = (ai,t - ai,min)/(\ ai,max - ai,min) * 4 + 1 \tag{2}$$

For the negative criterion (the bigger the value the worse the performance), the quantitative data were manipulated by formula (3).

$$Si,t = 5 - (ai,t - ai,min)/(ai,max - ai,min) * 4 \tag{3}$$

where,

ai,t:the value of technology *t* against criterion *i*.
ai,max: the maximum value of all the *ai,t*.
ai,min: the minimum value of all the *ai,t*.

The final score of a LCT was then calculated by formula (4) as below.

$$\text{Final scores} = \sum_{i=1}^{n} \text{Weighting coefficient } (i) * Si,t \tag{4}$$

Table 5
Final results of weighting coefficient.

Sub-criteria	Weighting coefficient
C11	0.36
C12	0.11
C13	0.09
C21	0.04
C22	0.07
C23	0.01
C31	0.17
C32	0.08
C33	0.07

4. Multi-criteria decision making model for selection of critical LCTs

4.1. Defining evaluation criteria

On the basis of literature review over the research papers and government reports, the evaluation criteria for LCTs are defined as shown in Table 3.

The environmental performance, technological performance

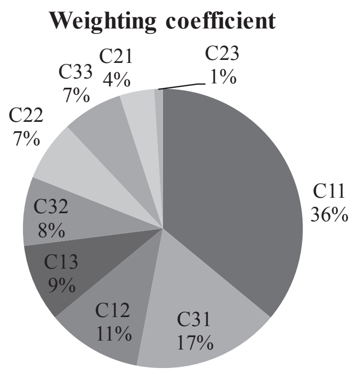

Fig. 4. The relative importance of each criterion.

and economic performance are the main criteria for evaluating the effectiveness of LCTs. Each of the main criteria consists of a number of sub-criteria.

The environmental performance indicates the overall environmental contribution of LCTs to the carbon reduction goal. It contains three sub-criteria: CO_2 emission reductions, other pollution reductions and energy saving. CO_2 emission reduction indicates the amount of CO_2 emissions reduced by applying LCTs. Besides, LCTs can also reduce other pollution including SO_2, NO_X, waste, sewage. Advanced LCTs can also reduce energy consumption in China, especially the use of fossil energy thus to reduce carbon emissions.

The technological performance shows the technical functionality and presents development status of LCTs. The technological maturity demonstrates development stages of LCTs. The technological reliability shows whether the performance of LCT is consistent and replaceable under expectable circumstances (Heo et al., 2010). It also emphasizes low risk in the technology transformation and industrialization process to achieve a stable development performance. The technological competitiveness consists of creativity and adaptability to market changes of technology.

The economic performance reflects the ratio of total output to input. This criterion directly affects the willingness of the technology importers' to import and apply LCTs in practice. The initial capital investment on the main technical equipment and infrastructure is represented by the cost of investment, which should be low in comparison with other technologies in order to reduce finance pressure of importers. The payback period is the period of time required to repay the original investment from net incomes. Those LCTs with lower input and higher output have greater advantages than others. The contribution to fiscal sustainability requires return on investment to be high as well as to promote the capital flow.

In all the criteria, the CO_2 emission reductions, energy saving, cost of investment and payback period are quantitative criteria, while the pollution reductions, technological maturity, technological reliability, technological competitiveness and contribution to fiscal sustainability are qualitative criteria.

4.2. Alternative LCTs list

The list of alternative LCTs for the three energy-intensive industries available for evaluation are shown in Table 4.

4.3. Evaluating of weighting coefficient

The weighting coefficient for every sub-criterion is calculated by formula (1), and the results are listed in Table 5.

The weighting coefficient demonstrates the relative importance of each criterion. The result reveals that the sum of the top three

Table 6
Original evaluation scores of LCTs.

	C11 (million t CO_2/a)	C12	C13 (million t ce/a)	C21	C22	C23	C31 (ten thousand yuan)	C32 (years)	C33
A1	0.45	4.12	0.17	4.14	4.15	4.23	3843	1.4	4.23
A2	10.30	4.28	3.90	4.21	4.26	4.18	16,000	3	4.29
A3	8.45	4.27	3.20	4.18	4.21	4.16	965	4.12	4.15
A4	10.50	4.35	4.00	4.26	4.28	4.14	22,000	1.5	4.32
A5	10.56	4.37	4.00	4.27	4.28	4.10	1600	3	4.19
A6	5.54	4.18	2.10	4.24	4.21	4.12	1810	0.5	4.27
A7	1.32	4.14	0.50	4.27	4.26	4.12	700	2	4.13
A8	1.53	4.12	0.58	4.25	4.19	4.19	380	0.97	4.17
A9	1.32	4.25	0.50	4.29	4.21	4.22	270	2	4.11
A10	2.38	4.22	0.90	4.18	4.14	4.17	4370	1	4.23
A11	4.49	4.25	1.70	4.27	4.24	4.13	800	2	4.18
A12	3.25	3.92	1.23	3.83	3.87	3.75	200	0.67	3.91
A13	2.38	3.92	0.90	3.85	3.88	3.71	3500	1	3.94
A14	1.19	3.86	0.45	3.94	3.89	3.83	120	0.2	3.95
A15	0.61	3.82	0.28	3.81	3.86	3.74	672	1	3.89
A16	1.32	3.89	0.50	3.91	3.85	3.76	100	0.17	3.9
A17	4.22	3.96	1.60	4.01	4.05	3.89	200	1	3.89
A18	6.30	3.92	2.40	3.93	4.01	3.84	950	1.5	3.92
A19	0.63	3.84	0.24	3.96	3.93	3.86	3000	4	3.91
A20	2.38	3.86	0.90	3.95	3.91	3.82	1000	3	3.86
A21	0.54	4.08	0.38	4.19	4.07	4.03	5800	3	4.11
A22	2.77	4.25	1.05	4.17	4.01	4.25	17,100	2.5	4.24
A23	0.41	4.04	0.15	4.02	4.07	4.17	17,000	2.5	4.26
A24	7.13	4.38	2.70	4.14	4.23	4.20	4000	2.5	4.19
A25	1.83	4.17	0.75	4.07	4.10	4.01	3000	2	4.13
A26	0.33	4.05	0.12	4.06	4.15	4.16	90,000	7	4.10
A27	1.72	4.19	0.65	4.20	4.16	4.23	12,000	2	4.26
A28	2.82	4.24	0.95	4.07	4.14	4.18	5000	3	4.17
A29	3.12	4.28	1.18	4.24	4.19	4.24	14,600	2	4.19
A30	1.25	4.16	0.51	4.17	4.05	4.09	20,100	4	4.21
A31	5.81	4.31	2.20	4.13	4.15	4.18	380	0.83	4.08

Table 7
Final evaluation scores.

Industry	ID	Score	Rank
The thermal power industry	A5*	4.64	1
	A4*	4.56	2
	A2*	4.48	3
	A3	4.20	4
	A6*	3.85	5
	A11	3.61	6
	A10	3.25	7
	A8	3.12	8
	A9	3.05	9
	A7	3.04	10
	A1	2.88	11
The cement industry	A18*	3.87	1
	A17*	3.54	2
	A12*	3.36	3
	A13	3.17	4
	A20	3.09	5
	A16	3.04	6
	A14	3.02	7
	A15	2.86	8
	A19	2.72	9
The iron & steel industry	A24*	4.04	1
	A31*	3.89	2
	A29	3.27	3
	A28*	3.21	4
	A22	3.15	5
	A25	3.1	6
	A27	3.03	7
	A21	2.81	8
	A30	2.78	9
	A23	2.71	10
	A26	1.93	11

criteria "C11 – CO_2 emission reductions" "C31 - Cost of investment" and "C12 - Other pollution reductions" is 0.64, accounting for 64% of all the criteria, as shown in Fig. 4 below.

They are the most important criteria among all nine criteria in the evaluation of LCTs. The criterion "CO_2 emission reductions" has the highest weighting coefficient according to expert's opinion, which is in line with the objective of this research.

4.4. Evaluation and selection of critical LCTs

The result from interview survey provides the final score are shown in Table 6 and the ranking of LCTs in the three industries are shown in Table 7.

The Quantitative data in Table 6 were extracted from the *National Extension Directory of the Key Energy Conservation Technology of China* issued by National Development and Reform Commission (NDRC) of China (National Development and Reform Commission of China, 2015). The experts from the three industries were again interviewed to select critical LCTs that had a greater impact on carbon mitigation in the three industries based on the final evaluation scores. The evaluation of experts on the qualitative performance of LCTs is shown in Table 6. In order to identify the critical LCTs, a consensus meeting was held with 10 experts with longest work experiences. The final scores after two rounds of consensus meeting are shown in Table 7.

The critical LCTs selected for each of the three industries are marked with a * sign in Table 7. The LCTs in each industry group vary in different extend, indicating uneven effectiveness across different technologies. A5 - The heat-electricity co-generation technical reform on condensing turbine in the thermal power industry has the highest score in all 31 LCTs due to its high CO_2 emission reductions and high energy saving capacity. The A26 - Low heating value blast furnace gas turbine combined cycle power plant in the iron & steel industry was given the lowest score, because of its least CO_2 emission reductions and highest cost of investment and longest payback period.

5. Discussion

The average scores of the LCTs in each of the three groups appear large differences. The average score of LCTs in the thermal power industry is 3.70, ranking the highest among the three groups. The average score of LCTs in the cement industry and the iron & steel industry are 3.19 and 3.08. The LCTs in the thermal power industry showed much higher average score compared with the other two industries, the average scores of the LCTs in the cement industry and the iron & steel industry had little difference.

For the thermal power industry, the critical LCTs include A5 - The heat-electricity co-generation technical reform on condensing turbine, A4 - Massive high-parameter lignite (brown) coal powder boiler technology, A2 - Gasification technology of pressurized pulverized coal and A6 - Performance improvement of steam turbine generation set. Although A3 - Deep recovery of waste heat from coal-fired power plant flue gas integrated optimization system in the thermal power has a higher score than A6 - Performance improvement of steam turbine generation set, it was not selected as critical LCTs. According to the experts' opinion on the consensus meeting, the main reason was that the turbine was widely used in the thermal power industry in China with relatively low efficiency in practice, which needed to be improved urgently. These four critical LCTs in the thermal power industry could reduce 36.90 million t CO_2 per year and save 14 million tce per year as shown in Table 6 A5 - The heat-electricity co-generation technical reform on condensing turbine used in the 125–600 MW condensing turbine has a large diffusion potential within the next five years. A2 - Gasification technology of pressurized pulverized coal could be employed in various industries with great carbon reduction potential, for example the chemical fertilizer industry, modern coal chemical industry and the thermal power industry.

Three LCTs: A18 - Optimization of the cement clinker burning system, A17 - High efficiency and energy saving powder technology, and A12 - Energy-saving efficient cement grinding technology were defined as critical LCTs in the cement industry. These three critical LCTs in the cement industry could reduce 13.77 million t CO_2 per year and save 5.23 million tce per year as shown in Table 6. A18 - Optimization of the cement clinker burning system could improve the utilization rate of the decomposition furnace, the heat transfer efficiency and the clinker cooling efficiency, saving more energy than traditional method. A17 - High efficiency and energy saving powder technology applies caged rotor high efficiency selective powder classification technology to achieve high accuracy, high efficiency separation and energy saving. A12 - Energy-saving efficient cement grinding technology optimized the internal structure of the ball mill and the grading plan to reduce its energy consumption.

For the iron & steel industry, A24 - Energy management system, A31 - Heating furnace blackbody technology to strengthen energy-saving, and A28 - Sintering flue gas recycling technology were critical LCTs for iron & steel industry. Experts in the iron & steel industry valued higher on A28 - Sintering flue gas recycling technology than A29 - Rotary cutter high blast hot stove energy saving technology for the reason that A28 - Sintering flue gas recycling technology has a greater development prospects with a better energy-saving and emission reduction in sintering process. These three critical LCTs in the iron & steel industry could potentially reduce 15.76 million t CO_2 per year and save 5.85 million tce annually as shown in Table 6. A24 - Energy management system employs information technology to manage enterprise' energy

system and reduces 1–3% annual energy consumption for the operators. A31 - Heating furnace blackbody technology to strengthen energy-saving installed high radiation coefficient black elements in the internal surface of steel rolling heating furnace to increase radiation efficiency and reduced energy consumption. Those LCTs in the three industries could play an important role in China's carbon mitigation. The promoting of these critical LCTs in China in the immediate term could also benefit environment protection and economic development.

6. Conclusions

This paper focused on the selecting of critical LCTs' for the three main energy-intensive and polluting industries in China, and provided theoretical support for short-term policy making. After expert surveys and consensus meeting, 10 critical LCTs in the three industries were identified, including 4 critical LCTs in the thermal power industry, 3 critical LCTs in the cement industry, and 3 critical LCTs in the iron & steel industry. It is suggested that the critical LCTs should be promoted and diffused in the next few years in order to achieve low carbon development and clean production of these industries.

In order to achieve the peak of carbon emissions by 2030 or sooner, the Chinese government should offer more political incentives to energy-intensive industries in promoting these critical LCTs with the best overall performance in clean production.

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